Early Holocene history of the west Greenland Ice Sheet and the GH-8.2 ka cal. yr BP event

A.J. Long, D.H. Roberts, S. Dawson[1]

Department of Geography, Durham University, Science Laboratories, South Road, Durham, DH1 3LE, United Kingdom

[1]School of Geography and Geosciences, University of St Andrews, Irvine Building, St Andrews, Fife KY16 9AL, Scotland, United Kingdom

Abstract

The margin of the Greenland Ice Sheet retreated rapidly during the first few thousand years of the Holocene. During this period of relative warmth, known as the Holocene thermal maximum, ice core records identify a significant short-lived cooling event at approximately 8.4-8.0 ka cal. yr BP (the 'GH-8.2 event') associated with a 5-8ºC fall in mean annual air temperature over the centre of the ice sheet. In this paper we constrain the history of the ice sheet margin in Disko Bugt (west Greenland) and that of a major ice stream, Jakobshavns Isbrae, during the early Holocene, which incorporates the interval of the GH-8.2 event. Our work is based on a new relative sea-level curve and minimum age estimates for the timing of deglaciation from two field sites, combined with a review of previously published research from the study area. We identify important differences in the chronology of ice margin recession during the early Holocene, most noticeably, the margin of Jakobshavns Isbrae retreated well inland of the adjacent ice sheet at this time. We conclude that the early Holocene 'Fjord Stade' moraines in Disko Bugt do not record a uniform ice sheet margin response to the GH-8.2 event. Rather, these moraines are diachronous and formed between c. 10 - 8 ka cal. yr BP, their age varying as a function of the interplay between topography and ice sheet / ice stream dynamics. We hypothesise that one cause for the lack of an identifiable response to the GH-8.2 event is because topographic controls dominated ice sheet behaviour at this time. In lowland areas, any increase in ice sheet mass balance was probably associated with an increase in calving rather than any major advance of a grounded ice sheet margin.

Corresponding author. Tel.: + 44-191-334-1913; fax: + 44-191-334-1801

E-mail address: A.J.Long@Durham.ac.uk

1. Introduction

Much palaeoglaciological effort is directed towards the reconstruction of large scale changes in ice sheet history associated with the retreat of ice sheet margins from their Last Glacial Maximum (LGM) positions (e.g. Funder and Hansen, 1996; Dyke and Prest, 1987; Conway et al., 1999; Andersen et al., 1995). Attention is also paid to ice sheet response to shorter-lived cold events such as the Younger Dryas (GS-1, Walker et al., 1999) and the Little Ice Age, during which intervals many ice masses slowed in their retreat or advanced. These short-lived episodes are of special interest since they provide an opportunity to examine the interaction between ice sheets, atmosphere and ocean dynamics over periods of rapid climate change.

As well as the GS-1 and the Little Ice Age, oxygen isotope records from the Greenland ice cores, GRIP and GISP2, reveal evidence for a pronounced short-lived climate perturbation during the early Holocene that saw air temperatures over the centre of the ice sheet fall by 5-7ºC (Alley et al., 1997; Alley and Ágústsdóttir, 2005). Dated to c. 8.2 ka cal. yr BP (hereafter termed the 'GH-8.2 event', Walker et al., 1999), this event is attributed to a temporary slow-down or shut-down of the North Atlantic thermohaline circulation triggered by the drainage of meltwater from large proglacial lakes in North America (Barber et al., 1999; Teller et al., 2002; Clarke et al., 2004). Despite the strong evidence of a climatic cooling in the ice cores, the response of the margin of the Greenland Ice Sheet (GIS) to this short-lived event is poorly understood.

In this paper we reconstruct the early Holocene deglacial history of Disko

Bugt, a large marine embayment in west Greenland. This study area is of particular interest since the ice sheet here is strongly influenced by the dynamics of the world's fastest flowing ice stream – Jakobshavns Isbrae – which drains a large portion of the Greenland Ice Sheet and discharges ice into Disko Bugt and Baffin Bay. Previous work has identified a widespread suite of early Holocene moraines in the eastern part of the bay (termed the 'Fjord Stade' moraines (Weidick, 1968)), that may possibly record an ice margin response to the GH-8.2 event (Long and Roberts, 2002). We test this hypothesis here with new observations from two field sites and, in so doing, explore ice sheet and ice stream dynamics during the early Holocene across the interval of the GH-8.2 event.

2. Ice sheet response to short-lived climate change

Map and air photographic evidence suggest that the GIS responds in a relatively rapid and predictable manner to climate cooling. In a study of 500 glacier lobes from c. AD 1650 onwards, Weidick (1968) shows that there were several advance phases during this interval, with many glaciers reaching their maximum extent and forming well-developed push moraines at c. AD 1850, AD 1890 and AD 1920. Weidick (1968, p.45) relates the latter of these to cold periods to meteorological records between AD 1880-1890 and AD 1913-1916, and argues that this correlation suggests a lag in the marginal response of the Greenland glaciers to climate change of between a few years and two decades. The study demonstrates that 94% of the glaciers studied responded in phase, despite their wide geographical distribution and individual glaciological characteristics. This apparent link between climate and ice margin response suggests that there should be clear evidence for other cooling events, such as that associated with the GH-8.2 event, recorded in the marginal glacial landforms of the GIS.

Other glaciological studies, however, show that ice margin position and moraine development can also be strongly influenced by topography, glacioterrestrial to glaciomarine/lacustrine transitions and sedimentological controls, as oppose to climatic factors (Boulton and Jones, 1979; Taylor et al., 2004). Hillaire-Marcel et al. (1981), for example, argue that the formation of the Sakami moraines (Younger Dryas age) of the Laurentide Ice Sheet in Quebec were controlled by changes in lake level and not climate. Moreover, modelling experiments by Hubbard (1999) shows that once the Younger Dryas Scottish ice sheet advanced into coastal waters its dynamics were essentially decoupled from direct climatic controls and instead became strongly dependent on topography and calving flux.

In western Greenland, geomorphological mapping shows a clearly defined sequence of prehistoric moraines that can be traced over hundreds of kilometres, the most prominent of which formed during the early Holocene 'Fjord Stade' (Weidick (1968), Fig. 1). Weidick (1974) suggests that the continuity of the Fjord Stade moraines indicates that they were probably associated with a temporary decrease in summer ablation and a short-lived change in ice sheet mass balance. Others, however, favour a topographic control for their origin, citing the abundance of these moraines within topographically restricted fjords (e.g. Warren and Hulton, 1990). Critical to evaluating the climatological significance of these moraines is the development of a reliable absolute chronology for their formation. Thus far, the main age control is provided by relative sea level (RSL) data collected from wide geographical areas (e.g. Weidick, 1968), although more detailed data do exist for some intensively studied sites such as Søndre Strømfjord (van Tatenhove et al., 1996).

3. The study area and previous research

Disko Bugt is a large (40,000 km^2) marine embayment between 68° 30’ N and 69° 15’ N and 50° 00’ W and 54° 00’ W (Fig. 1). The mainland bedrock geology comprises Precambrian gneisses, with Tertiary basalts on the island of Disko and parts of the Nuussuaq peninsula (Chalmers et al., 1999). Mean annual air temperature is c. -4°C and the bay is generally ice free between mid-April and mid-January. Water depths in Disko Bugt typically vary between 200 m and 400 m and may locally exceed 1000 m. At the LGM, Disko Bugt was fully occupied by grounded ice, with an enlarged Jakobshavns Isbrae extending offshore, onto the continental shelf of Baffin Bay (Funder and Hansen, 1996; Long and Roberts, 2003; Roberts and Long, 2005). Sometime before 10.5 ka cal. yr BP the margin of this ice stream became unstable and began to retreat into Disko Bugt, with calving into a deep (> 800 m) trough at the mouth of Disko Bugt, followed by rapid retreat to the shallower eastern part of the bay.

A series of prominent moraines that lie broadly parallel to the eastern coastline of Disko Bugt suggest that the ice sheet margin slowed or paused here during its rapid early Holocene retreat (Fig. 2). These moraines belong to the “Fjord Stade” moraine complex, one of a suite of moraines referred to above that can be traced across much of west Greenland between 5 km and 30 km from the inland ice, and that dates to c. 9.3 ka cal. yr BP (Weidick, 1968; Kelly, 1985). Long and Roberts (2002) reevaluated the age of this moraine at Orpissooq, the informal type site of the Fjord Stade in southeast Disko Bugt (Donner and Jungner, 1975) (Fig. 1) and suggested that here the moraines date from between 8.4 and 7.7 ka cal. yr BP. They cautiously suggested that the moraine may record an ice marginal response of the GIS to the GH-8.2 event, although they recognised that further dating evidence from elsewhere in Disko Bugt was needed to test this hypothesis fully.

Long *et al.* Figure 1

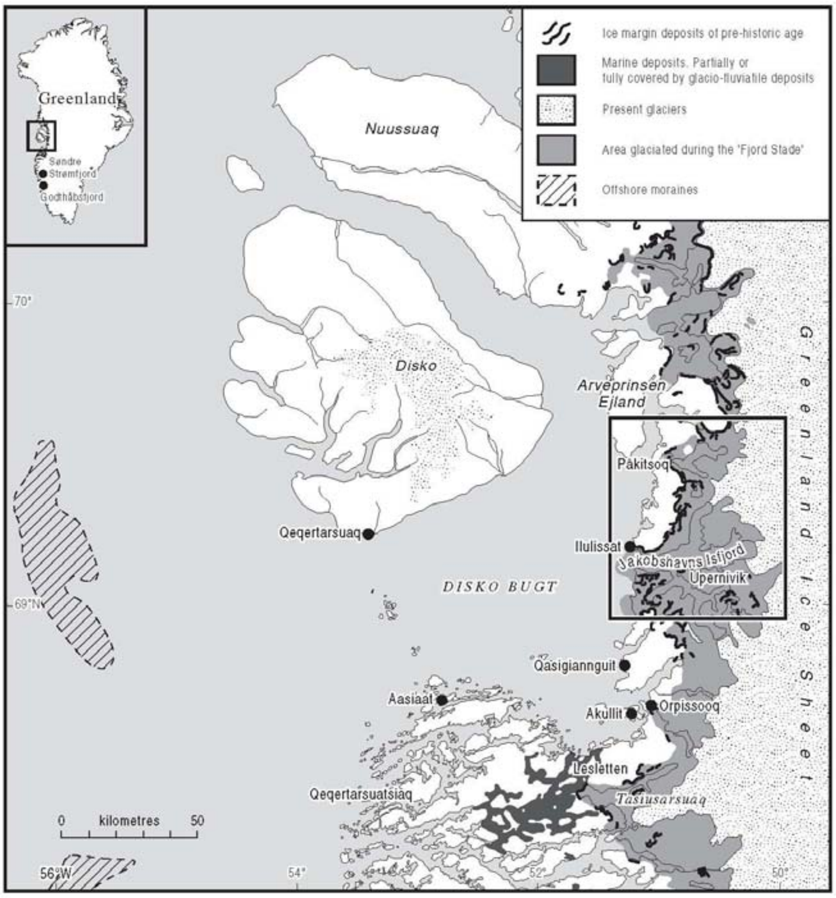

Fig. 1. Location map depicting the glacial landforms and deposits of Disko Bugt, west Greenland, modified from Weidick (1968) and including the location of offshore banks mapped by Brett and Zarudzki (1979).

Here we present new age controls on the early Holocene retreat of the GIS from two sites in Disko Bugt (Fig. 1). The first site is located at Upernivik, mid-way along Jakobshavns Isfjord and east of the extensive Fjord Stade moraines in the centre of the bay. This site provides a new RSL record that is used to review regional trends in sea level change and deglaciation. The second site is at Pâkitsoq, 30 km north of Jakobshavns Isfjord, where a cluster of lakes also constrains the age of the Fjord Stade moraine. When combined with the data from Orpissooq, these sites provide a broad north to south coverage of Fjord Stade moraines along the east coast of Disko Bugt and enable us to test more thoroughly the evidence for a regional ice sheet response to the GH-8.2 event.

Long *et al.* Figure 2

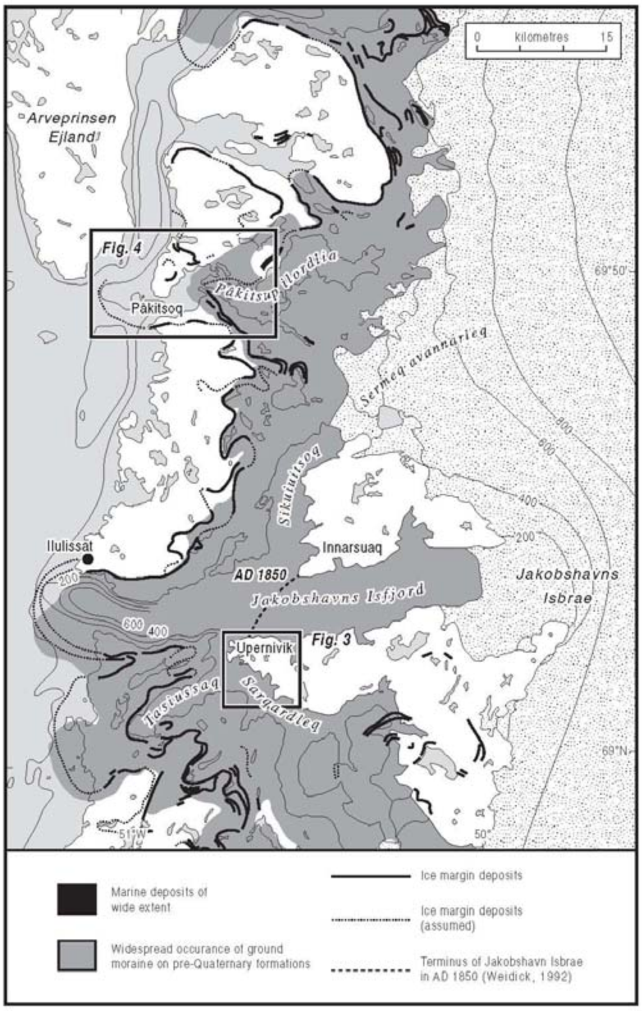

Fig. 2. Location of the two main study sites showing the Quaternary sediment distribution and former ice margin positions (from the Danish Geological Survey).

4. Techniques

We use three lines of evidence - the elevation and age of the marine limit (ML), RSL data from isolation basins, and glaciological mapping - to establish the timing and pattern of early Holocene ice sheet recession. The age of the ML provides a minimum estimate of the timing of deglaciation and can be established using RSL data or by dating the onset of organic accumulation in lakes above the ML. Our new RSL record developed from Upernivik is based on data collected from a staircase of isolation basins; natural rock depressions that were, at different times in their history, connected to or isolated from the sea as a result of RSL change. We cored these lakes with a Russian sampler from a boat, and collected sample cores for laboratory analysis using a piston corer. We determined elevations using closed levelling surveys with an EDM and a Sokisha level, with altitudes established with respect to mean sea level (MSL). At Upernivik we used tidal observations collected with a sea-bed pressure transducer referenced to local tidal predictions for Ilulissat, and at Pâkitsoq surveyed to the high water mark, also referenced to tide tables from Ilulissat. The tidal range in both field sites is c. 2.5 m. The sill elevations of the isolation basins are corrected to MSL based on the diatom assemblages preserved at the dated horizon in the sample cores (see Long et al., 1999). We measured the marine limit by surveying the lower limit of perched boulders in each study area.

Core material was prepared for diatom investigations using standard techniques (Palmer and Abbot, 1986) and diatom identifications were made with reference to Van der Werff and Huls (1958-1974), Hustedt (1957), Patrick and Reimer (1966, 1975), Hendey (1964) and Foged (1972, 1973, 1977). Diatom counts are expressed as a percentage of total diatom valves (%TDV) and full counts are available from the lead author on request. The chronology is based on Accelerator Mass Spectrometry (AMS) radiocarbon dates on thin (0.5 to 1 cm) bulk sediment slices of lake gyttja (Table I). The calibration program used is the INTERNET CALIB Rev4.4.2 (Stuiver et al., 1998) and all calibrated dates are cited with a two sigma age range. Dates on marine shells are taken from Rasch (1997) and have been corrected for isotopic fractionisation by normalising to a $\delta^{13}C = 0.0$ ‰ PDB.

5. Field sites

5.1 Upernivik

A suite of moraines at the outer part of the Jakobshavns Isfjord relate to a recessional position of the ice stream as it temporarily stabilised on a bedrock high to the immediate south of Ilulissat (Figs. 2 and 3). At Upernivik, mid-way along Jakobshavns Isfjord, a bedrock ridge (Asiarmuit) of gneiss bounds the southern limit of the fjord. This ridge rises 100 - 350 m a.s.l. and is breached by the Tasiussaq and Sarqardleq fjord systems. We selected the Upernivik site because of the abundant lakes that extend from present sea level to well above the marine limit. The site provides an excellent opportunity to establish the minimum age of the moraines at the head of Jakobshavns Isfjord, and to determine when the ice stream retreated from Disko Bugt into its bedrock trough.

5.2 Pâkitsoq

Pâkitsoq is a marine inlet in northeast Disko Bugt, to the southeast of Arveprinsen Ejland (Figs. 2 and 4). A prominent moraine at the constriction between Pâkitsoq and Pâkitsoq ilordlia marks the outer Fjord Stade ice margin in this area (Weidick, 1968). We cored one lake immediately inside, and two lakes outside of this moraine. Our sampling strategy was designed to establish a minimum age for the formation of the Fjord Stade moraines and, therefore, all of the sampled lakes lie close to the local marine limit.

6. Results

6.1 Upernivik

6.1.1 The marine limit

We measured the elevation of 27 perched boulders to the south of the Asiarmuit bedrock ridge (ML1) (Fig. 3). The average height of the lowest ten of these is 41.58 m ± 0.95 m. Comparable measurements at ML2, to the north of the bedrock ridge on Qajaa, yielded a value of 41.09 ± 1.83 m. There is, therefore, no difference in ML elevation on either side of the bedrock ridge.

6.1.2 Lakes above the marine limit

T7, 250 m a.s.l.

This lake lies 100 m below the summit of Asiarmuit. Morainic material above the lake on the summit slopes and ridge crest suggest that the lake was covered by ice at the last glacial maximum. The deepest sediment sampled from this lake is a dense grey silt sand (Fig. 5A). No sediment was analysed for their diatom content since the lake lies well above the ML. A 1 cm thick sediment slice from the base of the gyttja, between 876 - 875 cm, yielded an AMS age of 6910 ± 40 BP (7823 - 7662 cal. yr BP, Beta-178170).

T6, 175 m a.s.l.

This lake lies on a wide bedrock shoulder below the ridge that defines the southern margin of Jakobshavns Isfjord (Fig. 3). A short transect of four cores show c. 2.5 m of gyttja overlying a dense grey silt sand (Fig. 5B). A piston core was collected from the position of core 1, and a 1 cm thick sediment slice from the base of the gyttja, between 876 - 875 cm, yielded an AMS age of 6750 ± 40 (7673 - 7512 cal. yr BP, Beta-178169).

T5, 43.32 m a.s.l.

Eight boreholes show a c. 1.5 m thick deposit of gyttja overlying a dense grey silt sand (Fig. 5C). Water depths increase and the thickness of gyttja thins towards the centre of the lake, suggesting that some erosion of the lake sediments has occurred, perhaps because of stream-wash from the catchment that drains into this lake. A sample core was collected from the position of core 8. A single diatom sample from the lowermost grey silt sand is dominated by the freshwater taxa *Fragillaria sp*. No marine influence is present and a sample of gyttja, between 671.5-671 cm, yielded an AMS age of 7960 ± 40 (8996-8647 cal. yr BP, Beta-178168).

6.1.3 Lakes below the marine limit

T4, 31.64 m a.s.l.

T4 is a small lake that lies to the southeast of the Qajaa peninsula (Fig. 3). Steep bedrock slopes rise to the north of the lake. Five cores record a grey silt sand, overlain by a laminated silt gyttja and then a brown elastic gyttja which extends to lake bottom (Fig. 5D). Diatoms from the sample core show the isolation of this lake from the sea by an up-core decline in polyhalobous and mesohalobous taxa and an associated increase in frequencies of oligohalobous taxa above 920 cm (Fig. 6A). A sample of gyttja from 923-922 cm yielded an AMS date of 6760 ± 40 BP (7676-7513 cal. yr BP, Beta-178165).

T3, 25.72 m a.s.l.

This large lake is located to the north of Nuuluk (Fig. 3). No streams drain into it, and an overflow discharges directly into Tasiussaq via a bedrock sill. Two stratigraphic transects were completed, one of which is shown in Fig. 5E. A sample core from the position of core 8 contains poly- and mesohalobous diatoms in a lower silt sand, which are replaced above 791 cm by oligohalobous taxa as the lake was isolated from the sea (Fig. 6B). A sample of gyttja from 792-791 cm yielded an AMS age of 5980 ± 40 BP (6895-6677 cal. yr BP, Beta-178171).

T2, 12.20 m a.s.l.

This lake lies on a relatively flat terrace comprising extensively shattered bedrock (Figs. 3 and 5F). Diatoms from the sample core record basin isolation from the sea by an up-core increase in gyttja and a switch from poly- and mesohalobous taxa to oligohalobous taxa (Fig. 6C). A sample of silt gyttja between 658-657.5 cm, yielded an AMS age of 5060 ± 40 BP (5910-5715 cal. yr BP, Beta-178166).

T1, 1.61 m a.s.l.

This low-lying lake is located a short height above the present saltmarsh. The lake sill is buried by peat that coring and shallow excavations showed to comprise intact and fractured bedrock. The sediment sequence (Fig. 5G) comprises a grey silt clay that is overlain by a 1-4 cm thick laminated black silt gyttja, which passes upwards into a gyttja that extends to the lake bed. Diatoms from the sample core show an abrupt up-core replacement of poly- and mesohalobous taxa by oligohalobous taxa (Fig. 5D), something not uncommon in small, shallow lakes where water mixing is rapid on lake isolation. A 1 cm thick slice of gyttja from 292-291 cm, yielded an AMS age of 4150 ± 40 BP (4826-4548 cal. yr BP, Beta-178167).

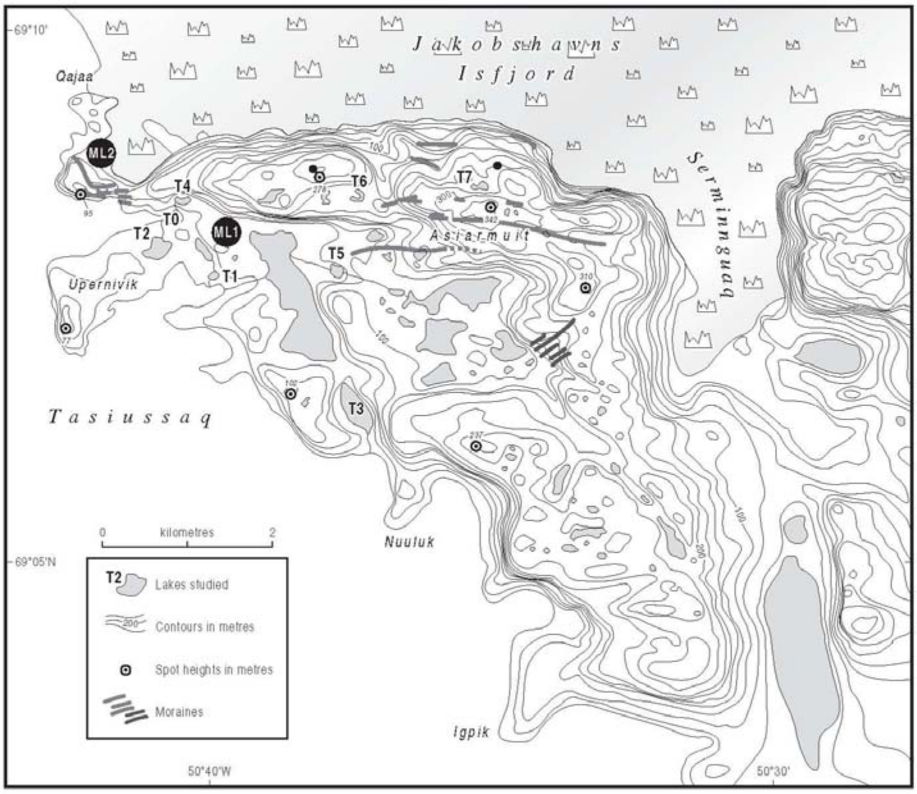

Fig. 3. Detailed map of the Upernivik field area, showing the lakes cored, the locations where the marine limit (ML) was determined, and prominent moraines and other glacial bedforms mapped (from Weidick, 1968; Roberts and Long, 2005).

T0, -3.33 m a.s.l.

A submerged bedrock ridge provides a sill that separates this tidal inlet from the open fjord. We levelled the height of this sill with six levelling transects, correcting our measurements for the change (0.28 m) in sea-level that occurred during the 61 minute period of observation using our tidal data. The lowermost sediments in the tidal inlet are a dense green silt sand with some angular pebbles, above which is a dark brown or black well-laminated silt gyttja, typically 10-20 cm thick, which is overlain by a 20-50 cm thick soft brown gyttja (Fig. 5H). Up-core the gyttja becomes black in colour and highly humified with a trace of silt, and passes into a thin (5-10 cm) dark grey organic-rich silt sand with some detrital organic matter. This is, in turn, overlain by a brown-grey sand silt with shells, fish bones, as well as detrital organic matter that extends to sea bed.

We collected a pair of overlapping piston cores from core 6 for diatom analysis and radiocarbon dating. Their diatom content clearly shows the isolation contact, towards the base of the sample core, and the ingression contact, towards the core top (Fig. 5E). Two samples of gyttja were dated from 1022-1021 cm and 997-996 cm, yielding ages of 3540 ± 40 BP (3957-3693 cal. yr BP, Beta-178172) and 1750 ± 40 BP (1812-1545 cal. yr BP, Beta-178173) respectively.

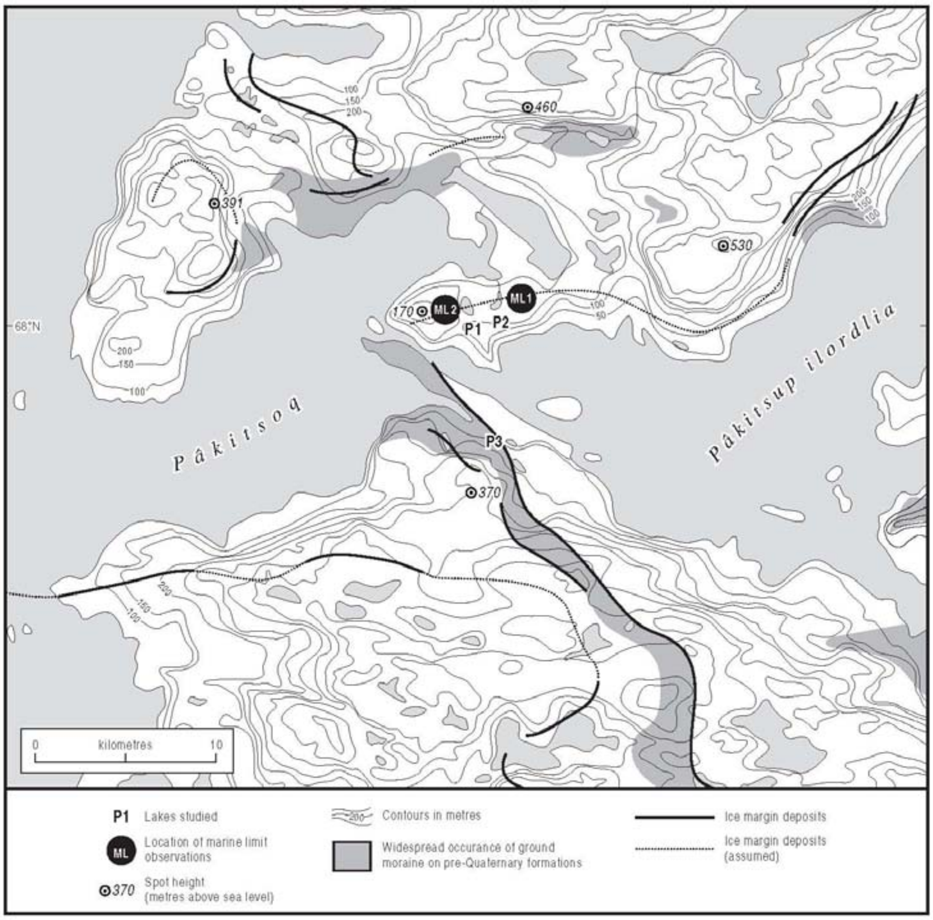

Fig. 4. Detailed map of the Paˆ kitsoq field area showing the lakes cored, the locations where the marine limit was determined, and prominent moraines and other glacial bedforms mapped, modified from Weidick (1968).

6.2 Pâkitsoq

6.2.1 The marine limit

We surveyed the marine limit by measuring the elevation of the lower limit of perched boulders at sites close to lake P1 and P2 (Fig. 4) to 36.32 ± 1.21 m a.s.l. (ML1, n = 7) and 36.55 ± 0.47 m a.s.l. (ML2, n = 8), respectively.

6.2.2 Lakes above the marine limit

P3, 41.21 m a.s.l.

This narrow, elongate lake lies just to the east of the Fjord Stade limit mapped by Weidick (1968). Six cores across the lake reveal a dense silt sand that is overlain by a thin grey brown silt gyttja and then a 1-2 m thick gyttja which extends to lake bottom (Fig. 5I). Diatoms from the silt gyttja (not shown) in the sample core are dominated by *Fragilaria* sp. and other oligohalobous and halophobous taxa, with no taxa suggesting any marine influence. A sample of gyttja from the base of the sequence (729-728.5 cm) was AMS dated to 6814 ± 38 BP (7720-7581 cal. yr BP, KIA-23028).

Long *et al.* Figure 5

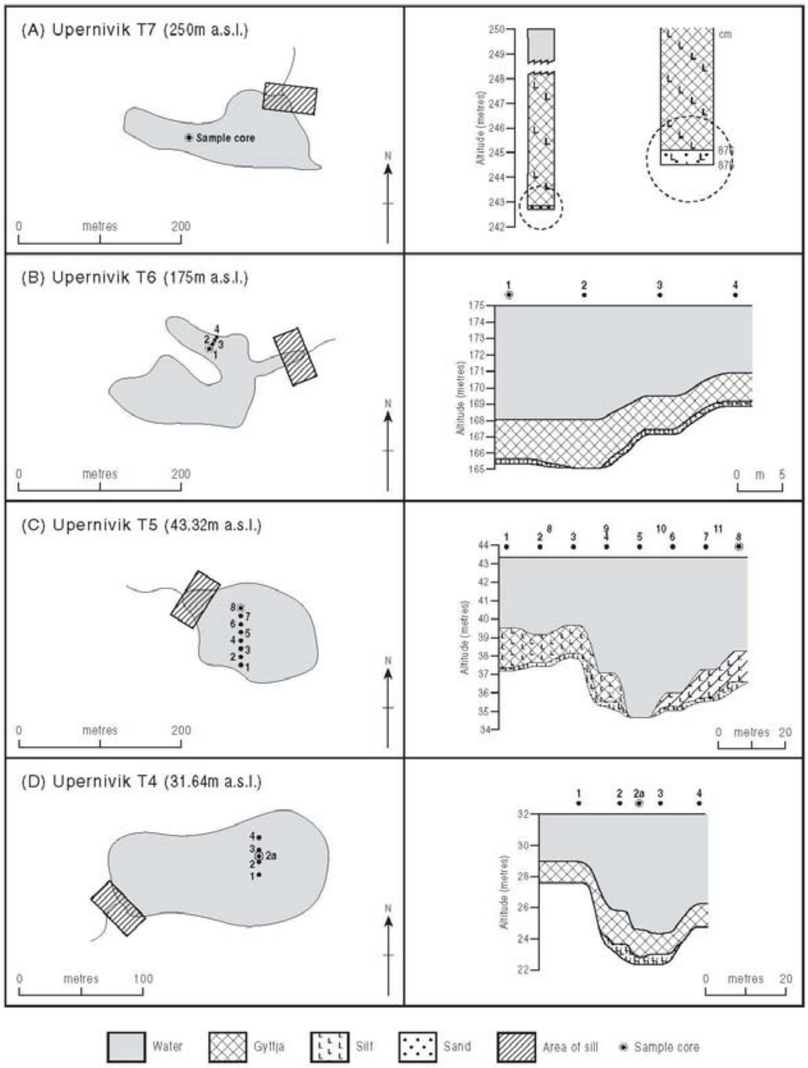

Fig. 5. The stratigraphy of the lake basins on Upernivik. (A) T7, (B) T6, (C) T5, (D) T4, (E) T3, (F) T2, (G) T1, (H) T0, (I) P3, (J) P2, (K) P1.

Long *et al.* Figure 5

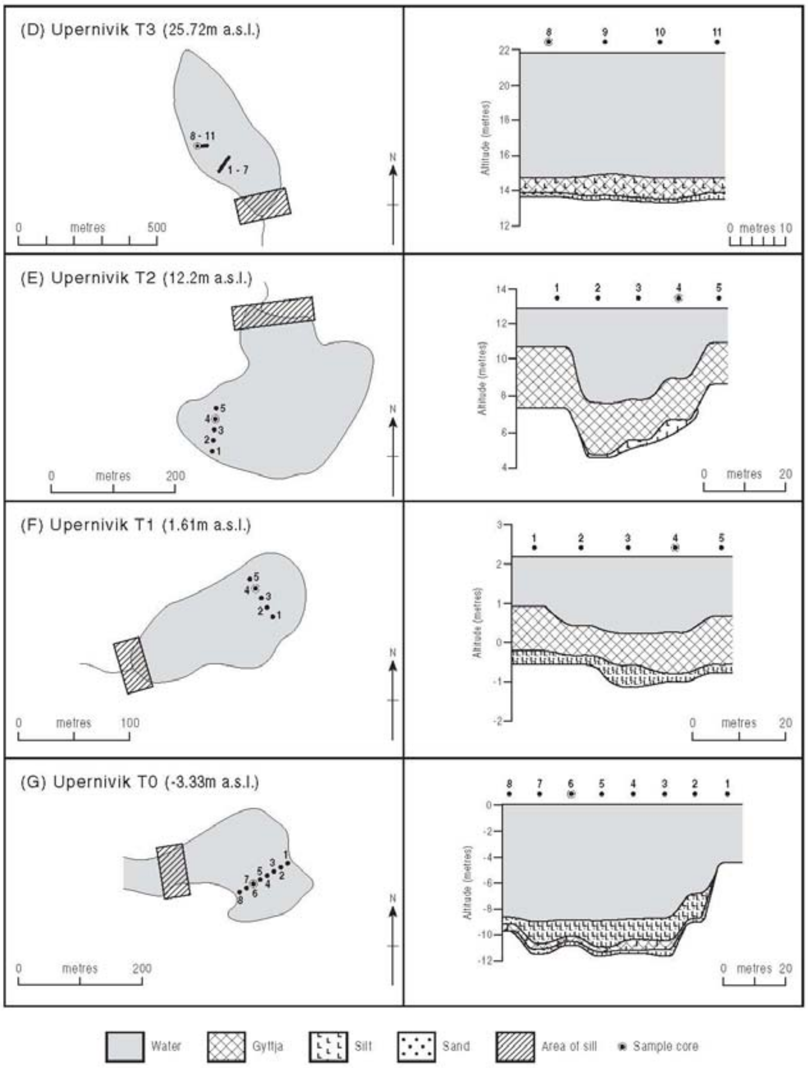

Fig. 5. (Continued)

Long *et al.* Figure 5

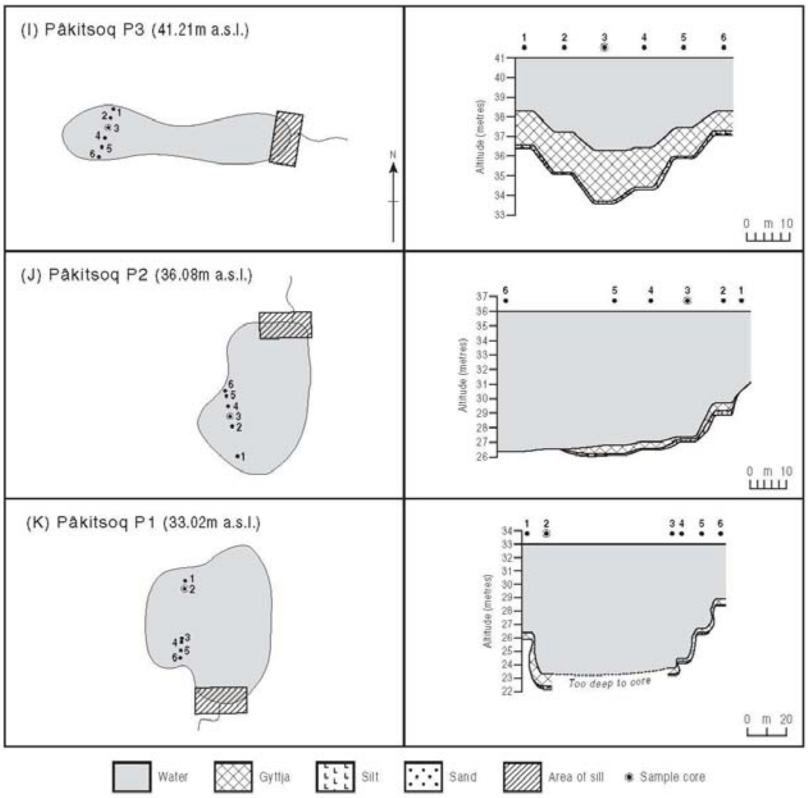

Fig. 5. (Continued)

P2, 36.08 m a.s.l.

P2 is located on a flat saddle of land that separates the inner part of Pâquitsoq from Pâqitsup ilodlia (Fig. 4). Four of the six boreholes in this lake show a dense grey sand silt which passes upwards abruptly into a gyttja, typically 75 cm thick, that extends to the lake bottom (Fig. 5J). There is no laminated transitional unit across the silt sand to gyttja transition, as is common in lakes below the marine limit. There are no diatoms in the silt, and those in the overlying gyttja (not shown) are dominated by freshwater types, notably *Fragilaria* spp. Thus, although this lake is very close to the marine limit, the sediments sampled contain no evidence for inundation by tidal waters. A 1 cm thick sediment slice from the base of the gyttja in the sample core yielded an AMS age of 6113 ± 121 BP (7262-6680 cal. yr BP, KIA-23027).

6.2.3 Lake below the marine limit

P1, 33.02 m a.s.l.

P1 lies close to and slightly below P2, c. 2 m to 3 m below the local marine limit (Fig. 4). Six boreholes record a dense grey silt with variable amounts of sand and clay overlain by gyttja. In core 2, a laminated silt gyttja separates these two units (Fig. 5K). Diatoms in the silt are dominated by the mesohalobous taxon *Scolioneis turmida*, and those in the overlying gyttja by freshwater taxa including high frequencies of *Fragillaria* spp. (Fig. 6F). This confirms that P1 lies below the marine limit. A 1 cm thick sediment slice from the base of the gyttja in the sample core yielded an AMS age of 6475 ± 30 BP (7429-7319 cal. yr BP, KIA-23026).

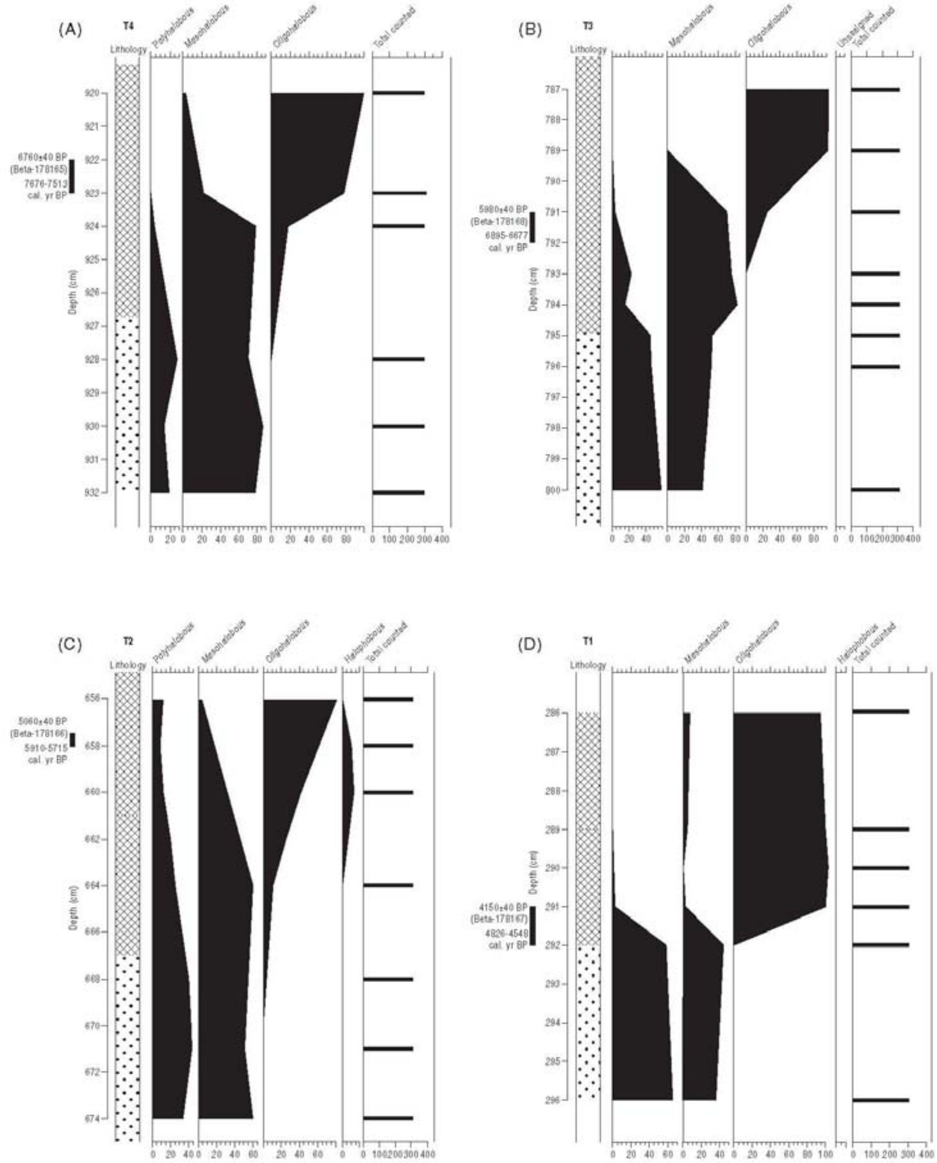

Fig. 6. Summary diatom diagrams from the lake basins on Upernivik and Paˆ kitsoq. (A) T4, (B) T3, (C) T2, (D) T1, (E) T0, (F) P1.

Long *et al.* Figure 6

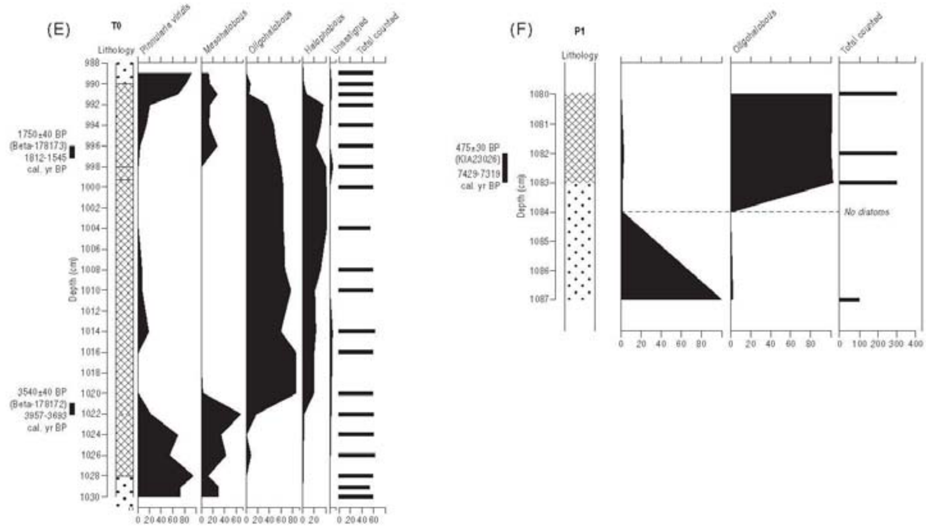

Fig. 6. (Continued)

6.3 Upernivik: the age of the marine limit and a new RSL curve for Jakobshavns Isfjord

The radiocarbon ages from the three highest lakes at Upernivik (T7, T6 and T5) provide minimum ages for ice retreat from the bedrock ridge that defines the southern margin of Jakobshavns Isfjord, and for the separation of Jakobshavns Isbrae from the adjacent ice sheet to the south. The date from T7 and T6 are very similar, and they indicate that these lakes were deglaciated after 7.8 – 7.5 ka cal. yr BP. However, the age for the onset of organic accumulation in T5 is about 1 ka cal. yrs older than those from T7 and T6. To help resolve these differences we use the RSL data from the remaining lakes in this study to estimate the age of the ML. Each basin records isolation from the sea and, when viewed together (Fig. 7), track MSL falling swiftly to intersect present shortly after 4.5 ka cal. yr BP. MSL continued to fall until at least 3.8 ka cal. yr BP, at which time T0 was isolated from the sea. T0 was fresh for about 2 ka cal. yr BP before being flooded once more c. 1.7 ka cal. yr BP. MSL fell to a minimum at Upernivik at c. 2.8 ka cal. yr BP, before rising at least 5 m to present. The switch from early and mid Holocene RSL fall to late Holocene RSL rise is a widespread phenomenon in Greenland associated with the onset of late Holocene re-growth of the ice sheet (Kelly, 1980).

Upwards linear extrapolation of the RSL data from T4 at 31.64 m to T5, at 43.32 m and just above the ML (Fig. 7), suggests that the ML here (c. 41 m a.s.l.) dates to c. 8.2 ka cal. yr BP. This estimate is close in age to the basal date from T5 just above the ML of c. 8.8 ka cal. yr BP. On this basis, we consider that 8.8-8.2 ka cal. yr BP is the best age estimate for the ML and a good approximation for the timing of local deglaciation at Upernivk.

7. Discussion

In the following sections we use the compilation of radiocarbon dates from Disko Bugt provided by Rasch (1997), updated with our recently collected data from this study and the Orpissooq area to; i) assess the age of the Fjord Stade moraines; ii) estimate the location of the ice sheet margin at the time of the GH-8.2 event and; iii) consider the implications of this work for our understanding of the controls on ice sheet margin during this short-lived event.

7.1 The age of the Fjord Stade moraines in Disko Bugt

7.1.1 Southeast Disko Bugt

The radiocarbon ages and the RSL curve proposed from Orpissooq indicate that the Fjord Stade moraine here dates to c. 8.5-7.7 ka cal. yr BP (Long and Roberts, 2002). The oldest date from each side of the moraine is c. 8.5 ka cal. yr BP from an isolation basin impounded by the Orpissooq moraine on Nuuk (7733 ± 56 BP, 8598-8406 cal. yr BP, AA-39665), and c. 8.0 ka cal. yr BP based on shells retrieved from a site inside the Fjord Stade limit at the head of Orpissooq (7210 ± 170 BP, 7696-8347 cal. yr BP, Hel-369) (Donner and Jungner, 1975) (Fig. 8).

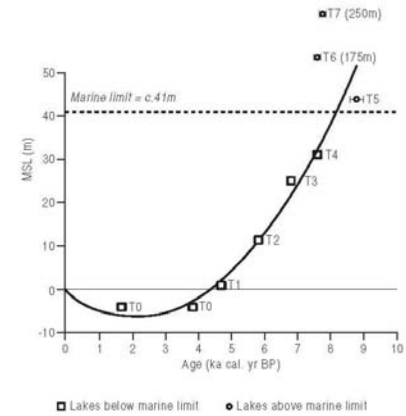

Fig. 7. Relative sea level graph depicting the index points from Upernivik. Y-axis errors are from Table 1 and X-axis errors are equal to the two sigma age range of each calibrated radiocarbon date. The smoothed line is a second order polynomial fitted to the lakes below the marine limit.

Long *et al.* Figure 8

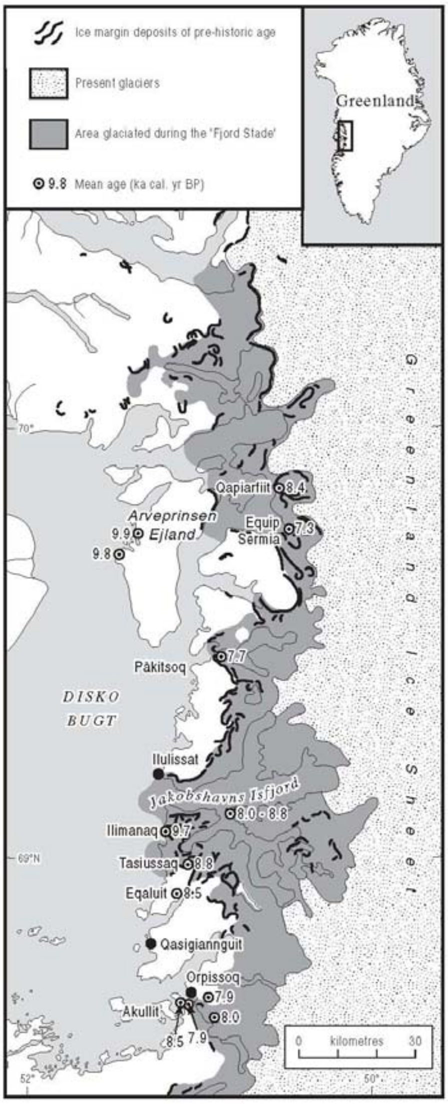

Fig. 8. Map depicting early Holocene radiocarbon dates from the eastern portion of Disko Bugt. Data are from Rasch (1997) supplemented with information from Long et al. (1999), Long and Roberts (2002), Long et al. (2003) and the present study.

7.1.2 Central Disko Bugt

At Eqaluit (Fig. 8), a site which lies to the west of the Fjord Stade limit, shells at 52 m a.s.l. provide a minimum date for deglaciation of c. 8.5 ka cal. yr BP (7650 ± 190 BP, 8977-8113 cal. yr BP, K-993) (Weidick, 1968). A short distance to the north, at Tasiussaq, a sample of basal gyttja from a lake on the surface of fluvio-glacial sands, just inside the Fjord Stade limit, provides an age of c. 8.8 ka cal. yr BP (7850 ± 190 BP, 9259-8215 cal. yr BP, K-987) (Tauber, 1968). At Ilimanaq, the oldest of five shell dates from below 40 m of c. 9.7 ka cal. yr BP (8680 ± 130 BP, 10,149-9329 cal. yr BP, K-2023) (Weidick, 1974). These shells lie just to the east of the Fjord Stade limit (Fig. 8). Lastly, our RSL data from Upernivik confirm that the Fjord Stade moraines to the west of this site must be older than c. 8.8-8.2 ka cal. yr BP. Together, these central Disko Bugt data show the Fjord Stade limit here dates from at least c. 9.7 ka cal. yr BP.

7.1.3 Northeast Disko Bugt

Our data show from Pâkitsoq (lake P1, Fig. 4) show that the Fjord Stade moraine here formed before c. 7.7 ka cal. yr BP, based on the date of 6814 ± 38 BP (7720-7581 cal. yr BP, KIA23028). Further north, two shell samples from Equip Sermia and Qapiarfiit (Fig. 8) inside the Fjord Stade limit, yield dates of c. 7.3 ka cal. yr BP (6420 ± 110 BP, 7566-7030 cal. yr BP, K6373) (Rasch, 1997) and c. 8.4 ka cal. yr BP (7600 ± 110 BP, 8601-8170 cal. yr BP, K3663) (Böcher and Fredskild, 1993) respectively.

The chronology from each of the three areas discussed above indicates that the Fjord Stade moraines in Disko Bugt are diachronous and do not record a distinct ice margin response to the GH-8.2 event. However, because the number of radiocarbon dates is low, especially in the northeast of the study area, and most were collected for other purposes than dating these moraines, we now use RSL and marine limit data to explore further the age of these moraines.

7.1.4 Relative sea-level changes and the Fjord Stade moraines in Disko Bugt

The new RSL graph from Upernivik is complementary to that developed previously from the Orpissooq area (Fig. 9). However, the marine limit varies significantly along the eastern shores of the bay, with a maximum elevation of >100 m a.s.l. in outer coastal areas but dropping steeply to between 60 m and 40 m a.s.l. across the Fjord Stade moraines (Rasch, 2000; Long and Roberts, 2002). This steep drop in ML elevation provides strong evidence that the ice sheet slowed in its retreat (or paused, or even readvanced) as the ice sheet reached the eastern shores of Disko Bugt. Because the RSL histories between areas in east Disko Bugt are broadly similar, we can use variations in the height of the ML as an indicator of the relative timing of local deglaciation. A further test of the age of these moraines is therefore possible by examining the elevation of the ML at sites where the Fjord Stade moraines intersect the coast; if the moraines are similar in age, then their associated marine limits should also be similar.

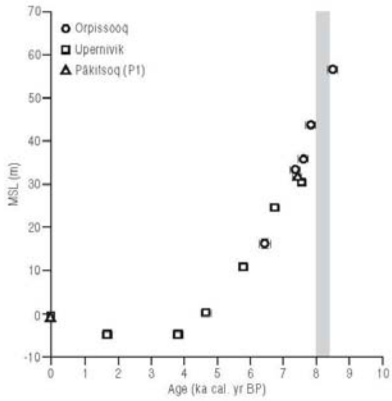

Fig. 9. Relative sea level graph from Upernivik, Orpissooq and Paˆ kitsoq. X and Y axis errors are as for Fig. 7. Only dates from isolation basins are shown. The shaded area covers the period of the GH-8.2 event.

The elevation of the marine limit in east Disko Bugt is shown in Fig. 10. This is based on the review by Rasch (2000), modified and supplemented by our observations at Orpissooq (Long and Roberts, 2002), Upernivik, Pâkitsoq and Arveprinsen Ejland (Long et al., 1999). According to Rasch (2000), typical height uncertainties associated with the observations he reports are ± 5 m. This map shows that the height of the marine limit varies significantly with respect to the Fjord Stade moraines. In southeast Disko Bugt, the marine limit at the Fjord Stade moraine is relatively low at c. 54 m a.s.l. Further north, in the Ilulissat area, the marine limit is higher, at c. 94 m a.s.l. immediately west of the Fjord Stade moraines. At the Pâkitsoq study site, the limit is between 36 m and 40 m a.s.l. These spatial variations are comparable with the suggested diachroneity of the Fjord Stade moraines discussed above and support an age model in which ice retreated from central Disko Bugt ahead of ice to the north and south of the bay.

The spatial variations in marine limit elevation shown in Fig. 10 show that the limit is at its highest at sites adjacent to major fjord mouths. Thus, high limits occur to the north of Arveprinsens Eijland, where ice would have drained via Torssukatak into Vaigat, and also in the south of the island at the mouth of Atâ Sund. High limits also occur at Qasigiannguit and at the entrance to Lakesebugt. Some of these height differences may reflect variations in wind/wave exposure, but the overall height range of the marine limit associated with the Fjord Stade moraines (54 m to 94 m a.s.l.) must reflect real differences in their age. These differences suggest that, as with Jakobshavns Isbrae, the mouths of these major fjords became ice free well before their intervening interfluve areas.

Long *et al.* Figure 10

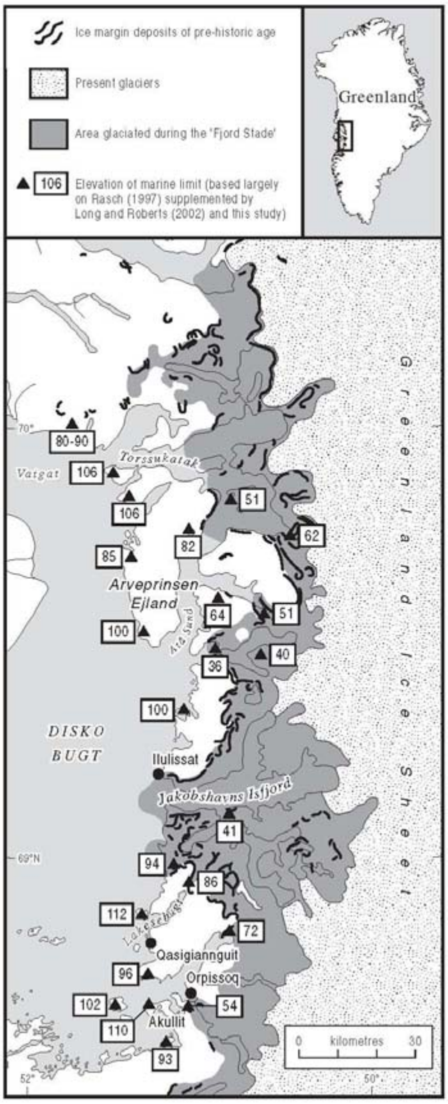

Fig. 10. The marine limit in eastern Disko Bugt based on Rasch (2000), Long et al. (1999), Long and Roberts (2003) and this study. Elevations are in metres above mean sea level. Typical height errors are75m (Rasch, 2000).

7.2 The location of the ice sheet margin at the time of the GH-8.2 event

In Section 7.1.3 we rejected the hypothesis that the Fjord Stade moraines record a GH-8.2 event ice margin. However, it should be possible, given our knowledge of the RSL history of the area (Fig. 9) and the elevation of the marine limit (Fig. 10) to estimate the general location of the ice sheet margin at the time of this event. We see from the former that the age of the GH-8.2 event (defined as between 8.4 and 8.0 ka cal. yr BP) relates to a MSL elevation of between c. 45 and 55 m a.s.l. Thus, those sites with a marine limit above 55 m probably lay outside the ice margin at the time of the GH-8.2 event. Figure 10 demonstrates that marine limits in this height range are entirely restricted to the inner parts of the fjords in east Disko Bugt. In all instances the ice sheet margin at the time of the GH-8.2 event was at or inside (i.e. east of) the outer limit of the Fjord Stade moraines.

7.3 Controls on ice sheet dynamics at the time of the GH-8.2 event

As noted above, the GH-8.2 event was associated with an initial, probably sub-decadal, abrupt drop in air temperatures and snow accumulation over the centre of the Greenland Ice Sheet. This was followed by a one to two century period of recovery to near pre-event conditions. In a recent review of this event, Alley and Ágústsdóttir (2005) note that glaciers in several parts of the northern hemisphere, including Scandanavia (Dahl and Nesje, 1994; Nesje et al., 2001; Seierstad et al., 2002), Alaska (Denton and Karlén, 1973) and coastal British Colombia (Menounes et al., 2004) all experienced short-lived advances at this time. Why then, is there no obvious marginal response of the GIS in Disko Bugt to this event?

One possibility is that the magnitude of the event was simply too short-lived to reverse the trend of early Holocene ice margin retreat and mass balance loss. During the run-up to the GH-8.2 event, the GIS as a whole was experiencing a significant mass balance deficit driven by the warmer temperatures of the thermal maximum (Kaufman et al., 2004) as well as significant ice loss via calving. In Disko Bugt, the ice sheet margin had retreated from the outer coast to Ilulissat at an average rate of c. 110 m yr^{-1}, based on minimum ages for deglaciation from the outer and inner parts of the bay (Long and Roberts, 2002). This rapid retreat agrees with the pattern of modelled ice volume loss from Greenland during the early Holocene by Tarasov and Peltier (2002). In the Søndre Strømfjord area, for example, their GrB model predicts ice thinning from 1100 m to 400 m between 10 and 8 ka cal. yr BP and a reduction in ice volume of the entire ice sheet from c. 0.4 to $<0.3\ 10^{16}\ m^3$. Against this trend, it appears that the GH-8.2 event was simply too short-lived to have a major impact on ice margin retreat.

The absence of a well-defined ice margin response to the GH-8.2 event may also be because much of the ice margin at this time was loosing mass to the ocean via calving. As discussed above, at this time the lowland ice margin in Disko Bugt was nested in a series of topographically restricted fjords (Warren and Hulton, 1990; Roberts and Long, 2005). In these settings ice discharge would have been strongly controlled by calving, a process that is in general more closely linked to water depth and fjord topography than climate (Pelto et al., 1989; Pelto and Warren, 1990; Long and Roberts, 2003).

These considerations emphasise the importance of the magnitude and duration of the event, antecedent mass balance history, and the significance of topographic setting in controlling ice sheet response to short-lived climate events. The discussion also highlights a strong geographical sampling bias in our work, and that of others working on the margins of marine-based ice sheets. By relying on data from coastal settings we have elected to construct an ice sheet chronology from environments that are known to be sensitive to non-climatic factors. Indeed, one of the original arguments Weidick (1968) uses for a climate origin of the Fjord Stade moraines is their continuity across interfluve areas where topographic controls can be less obvious. Therefore, an important challenge for those interested in examining ice sheet response to short lived climatic events is to map and date ice margin deposits in settings where such topographic controls are minimised.

8. Conclusions

This paper addresses the dynamics of the Greenland Ice Sheet during the early Holocene, including the interval of the GH-8.2 event. Using new data from two field sites at Upernivik and Pâkitsoq, together with previously published data from Disko Bugt, we test the hypothesis that a suite of early Holocene moraines (the Fjord Stade moraines (Weidick, 1968)) record an ice margin response to the GH-8.2 event.

A new RSL curve from Upernivik, a site located in central Disko Bugt mid-way along Jakobshavns Isfjord, tracks relative sea level falling from the marine limit (c. 43 m a.s.l) to present sea level between c. 8.8-8.0 and 4.5 ka cal. yr BP. Relative sea level continued to fall until c. 2.8 ka cal yr BP, after which it rose by c. 5 m to present. This record demonstrates that Jakobshavns Isbrae had retreated inland from a calving margin at the mouth of Jakobshavns Isfjord by c. 8.8 ka cal. yr BP.

A review of early Holocene radiocarbon dates from Disko Bugt suggests that the Fjord Stade moraines are 1-2 ka cal. yrs older in the Jakobshavns Isbrae part of the bay compared with areas to the north and south. Thus, during the early Holocene Jakobshavns Isbrae retreated inland ahead of the remainder of the ice sheet margin in Disko Bugt. The general trend of the Upernivik RSL data is similar to that previously reported from elsewhere within Disko Bugt. Accordingly, we approximate the timing of local deglaciation and, by extrapolation, the age of the Fjord Stade moraines by examining the age and elevation of the marine limit across the study area. The highest marine limits (c. 100 m a.s.l.) occur at the mouths of the major fjords that drain into the eastern part of Disko Bugt. These areas became ice free first during the early Holocene. In general, marine limits are lower in southeast and northeast Disko Bugt compared with those in the centre of the bay near Jakobshavns Isfjord. This provides further support for the hypothesis that the oldest Fjord Stade moraines occur in the central part of Disko Bugt.

We are unable, based on the data presented in this paper, to resolve a distinct ice sheet margin response to the GH-8.2 event in Disko Bugt. There is no clearly identifiable set of glacial landforms from this period that can be traced on geomorphological or chronological grounds across the study area.

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Figure 7 Relative sea level graph depicting the index points from Upernivik. Y-axis errors are from Table I and x-axis errors are equal to the two sigma age range of

each calibrated radiocarbon date. The smoothed line is a second order polynomial fitted to the lakes below the marine limit.

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Table 1. List of radiocarbon ages from Upernivik and Pâqitsoq (Disko Bugt, west Greenland). MSL = mean sea level.

Basin	Laboratory code	^{14}C age ± 1σ	δ ^{13}C PDB ‰ ± 0.1	Cal. yrs BP ± 2σ	Max. sill altitude (m above MSL)	Min. sill altitude (m above MSL)	Mid sill altitude (m above MSL)	Reference water level	Indicative meaning (m)	MSL (m)	Type of date
T7	Beta-178170	6910 ± 40	-20.5	7662-7823	Not measured	250	Not relevant	None	None	Not relevant	AMS
T6	Beta-178169	6750 ± 40	-21.4	7673-7512	Not measured	175	Not relevant	None	None	Not relevant	AMS
T5	Beta-178168	7960 ± 40	-20.7	8647-8996	Not measured	43.32	Not relevant	None	None	<43.32	AMS
T4	Beta-178165	6760 ± 40	-26.0	7513-7676	31.72	31.64	31.56	MHWST-HAT	1.05 ± 0.28	30.59	AMS
T3	Beta-178171	5980 ± 40	-24.3	6677-6895	25.98	25.72	25.47	MHWST-HAT	1.05 ± 0.32	24.67	AMS
T2	Beta-178166	5060 ± 40	-16.5	5715-5910	12.57	12.20	11.93	MHWST-HAT	1.05 ± 0.35	11.15	AMS
T1	Beta-179167	4150 ± 40	-18.4	4548-4826	1.94	1.61	1.29	MHWST-HAT	1.05 ± 0.33	0.56	AMS
T0	Beta-178172	3540 ± 40	-25.3	3693-3957	-3.16	-3.33	-3.51	MHWST-HAT	1.05 ± 0.32	-4.38	AMS
T0	Beta-178173	1750 ± 40	-23.8	1545-1812	-3.16	-3.33	-3.51	MHWST-HAT	1.05 ± 0.32	-4.38	AMS
P1	KIA-23026	6475 ± 30	-19.05	7319-7429	33.02	33.02	33.02	MHWST-HAT	1.05 ± 1.00	31.97	AMS
P2	KIA-23027	6113 ± 121	-21.03	6680-7262	Not measured	36.08	Not relevant	None	None	Not relevant	AMS
P3	KIA-23028	6814 ± 38	-16.14	7270-7581	Not measured	41.21	Not relevant	None	None	Not relevant	AMS